by QC software. Qualitative review of the data was always performed by a trained meteorologist who was thoroughly familiar with both the measurement systems and the meteorological patterns that were expected to be revealed in the data.

Processing of the Rawinsonde Data

At the conclusion of each sounding, the upper air operators made two back-up copies of the sounding data on floppy diskettes. The operators also completed a sounding log form, which was used to document information necessary to complete the processing of the data. At the conclusion of each IOP, one copy of the data and the sounding log was transferred to the field operations center in Waukegan. The second copy remained at the site for the duration of the field study.

Receipt of the data at the operations center was recorded on a chain-of-custody/quality control (COC/QC) form. The date the data were received and the initials of the person logging the data into the upper air data base (usually STI's rawinsonde data manager) were recorded on the form. The data files were then copied to a data processing computer and a new back-up copy was made before further processing was performed. The copies of the sounding logs and COC/QC forms were placed in a data processing log book. A separate log book was maintained for each site.

Before Level 1 validation of the data was performed, the sounding data were converted to a common data format (CDF). The CDF included fields for elapsed time, altitude, pressure, temperature, relative humidity, dew point temperature, wind height, wind direction, wind speed, and "place holders" for the quality control flags that would be assigned to each variable when the Level 1 review of the data was completed. Adjustments were made to reported pressures and altitudes as needed, based on the calibrations of the station barometers that were made before and after each IOP. Additional processing was required for the ozone sounding data, using software provided by VIZ. The VIZ software computed ozone concentrations, reported as parts per billion (ppb), as a function of altitude using the measured pressure, temperature, pump flow rate, and electrical current generated by the ECC ozonesonde.

The next step in the data processing was to use an STI software package to screen the soundings for outliers and rates-of-change that exceeded expected conditions. The software that performed this task generated a list of the data points that had failed to pass the QC screening checks specified in the program. A plot of each sounding was also produced to aid the meteorologist who would perform the final review of the data.

Once the software screening of the data was completed, a trained meteorologist reviewed each sounding. Based on his or her experience and using the results of the QC screening program and the plot of the sounding data, the reviewer assigned final quality control flags to each data point in a sounding. The following QC flags were used:

0	Valid data
1	Estimated data
2-6	Not used
7	Suspect data
8	Invalid data
9	Missing data

The meaning of these QC indicators was as follows:

> Valid data (QC flag = 0) were observations that were judged accurate within the performance limits of the instruments.

> Estimated data (QC flag = 1) were observations that required additional processing because the original values were suspect, invalid, or missing. Estimated data were computed from standard upper air algorithms, from patterns or trends in the data (e.g., interpolation), or they were based on the meteorological judgement of the reviewer.

> Suspect data (QC flag = 7) were observations that, in the judgement of the reviewer, were in error because their values violated reasonable physical criteria or did not exhibit reasonable consistency, but a specific cause of the problem was not identified (e.g., excessive wind shear in an adiabatic boundary layer).

> Invalid data (QC flag = 8) were observations that were judged inaccurate or in error, and the cause of the inaccuracy or error was known (e.g., winds computed from erroneous Loran data). In addition to the QC flag signifying the data as invalid, the data values themselves were replaced with an invalid data indicator (-980.0)

> Missing data (QC flag = 9) were observations not collected; in addition to a QC flag signifying missing data, the data values themselves were assigned a missing value indicator (-999.0).

Quality control flags were assigned to derived parameters (e.g., altitude, dew point, wind speed, wind direction) based on the "worst case" QC flags assigned to the observations used to calculate the derived variables. For example, if a "valid" temperature measurement (QC flag = 0) but a "suspect" pressure observation (QC flag = 7) were used to calculate an altitude, the QC flag assigned to the altitude variable signified that it too was "suspect" (QC flag = 7).

The use of the QC flags identifying data as estimated (QC flag = 1) was generally confined to the so-called "wind height", which refers to the mid-point of the layer over which the winds were averaged. Due to a "bug" in VIZ's data acquisition software, many of these heights were erroneous (the wind data were not affected by this problem). New wind heights were computed by interpolating the balloon altitude data over 15 second intervals (the wind averaging interval; see Table 3). The new wind heights were accurate to within 2 to 5 meters, depending on the ascent rate of the balloon.

At each step during the data processing, a back-up was made of each version of the data. Likewise, all the data processing activities and the results of the validation process were documented in the COC/QC log maintained for each sounding. The majority of the efforts in the Level 1 validation of the rawinsonde data collected during the two IOPs was completed before the end of the field study. Some additional processing and a final review of the data was performed at STI before the data were delivered to the LMOS Data Manager. The final processing and review of the ozone sounding data was completed late in the Fall of 1991.

Processing of the Radar Profiler Data

The steps in the processing of the radar profiler and RASS data were similar to those described in the previous section, except that the majority of the work to complete the data processing and validation was performed after the field study.

Early in the morning of each day of the field study, the network hub computer at the operations center polled the profilers and down-loaded the previous 24 hours of wind and temperature data. Software running on the hub computer automatically plotted time-height cross-sections of the data and generated a list of the data received. A field technician examined the data later in the morning and reported any apparent problems to a field engineer, who would perform any corrective actions required. A copy of the data plots was also sent each morning via facsimile to STI's radar profiler data manager in Santa Rosa for review.

As mentioned previously, the technician visited each profiler site routinely and made back-ups of the data. The technician prepared a second back-up at the operations center. One copy of the data, along with appropriate quality control documentation, was then sent to STI. When the data were received in Santa Rosa, they were logged into the radar profiler data base by the data manager. A COC/QC form was prepared for each day's data. These forms were maintained in site logs at STI.

As was the case for the rawinsonde data, the first step in the Level 1 validation of the profiler data was to convert the observations to a common data format. The radar profiler CDF included fields for time, altitude, wind speed, wind direction, and "place holders" for the quality control flags that would be assigned to each variable when the Level 1 review of the data was completed. A separate set of data files with their own CDF was generated for the RASS data.

The next step was to subject the data to a QC screening software package that was originally developed by researchers at NOAA/ERL/WPL and subsequently modified by STI for application to the LAP-3000 data[9]. Referred to as the Weber-Wuertz (W-W) editor, this program used pattern recognition techniques to check for spatial and temporal consistency in the data and to flag apparent outliers in the data. After the data had been processed by the W-W editor, a new set of time-height cross-section plots of the data was prepared. The data were then reviewed by the data manager, who was a trained meteorologist thoroughly familiar with profiler principles and operations.

Based on the final review of the LAP-3000 data, QC codes were assigned to each data point by the reviewer. The same codes previously described for the rawinsonde data were used for the radar profiler wind and temperature data. Each step in the processing and review of the data was documented. Due to time and budget constraints, data collected during the IOPs and one other period (June 18-21, 1991) were brought to Level 1 validation. The remaining data were converted to the CDF, screened by the W-W editor, and reviewed by the data manager, but the degree of this review was not as complete as one would normally perform for full Level 1 validation. At the conclusion of this process, all of the data in their final CDF were delivered to the LMOS Data Manager.

EXAMPLES OF PRELIMINARY ANALYSES OF THE UPPER AIR DATA

One of the first steps in the analyses of the LMOS upper air data is to continue the validation of the observations via the application of Level 2 review techniques. For the upper air data bases, Level 2 validation involves examining the spatial and temporal consistency of the rawinsonde and radar profiler data both separately and jointly. In the course of applying Level 2 techniques to the data, conditions are often discovered that lead to improved understanding of the meteorological mechanisms affecting air quality conditions.

One such analysis of the upper air data is shown in Figure 2, which is an isentropic analysis showing a time-height cross-section of potential temperature and winds measured by the Zion 2-Mile rawinsonde station during the second IOP (July 16-18, 1991). Plots of this type were prepared from each station's data to examine the temporal consistency of the rawinsonde observations.

An unusual event appeared to be revealed by this analysis beginning at approximately 0300 CDT on July 17, 1991 and continuing until approximately 1500 CDT later that same day. The isentropes (isopleths of constant potential temperature) indicated that rapid cooling occurred in a mid-level layer from approximately 3500 m msl to 4500 m msl beginning at 0300 CDT on July 17. A similar cooling pattern appeared in the lower levels (approximately 700 m msl to 2500 m msl) beginning 3 hours later. Abrupt warming then apparently occurred in the mid-level layer between 0900 CDT and 1200 CDT; likewise, the lower layer appeared to experience comparable warming between 1200 CDT and 1500 CDT. The isentropes also indicated that the inversion capping the mixed layer descended from approximately 1400 m agl at 1500 CDT on July 16 to approximately 400-500 m agl by 0600 CDT July 17, when the rapid cooling in the lower layers began.

The wind profiles showed that southwesterly winds in the mixed layer on July 16 gave way to westerly to northwesterly winds on July 17. At 1200 CDT on July 17, winds from the north-northeast appeared in a layer from roughly 400 m agl to 1200 m agl, accompanying the cooling of the lower levels. However, by 1500 CDT, winds from the southwest were again observed in the lower levels, which coincided with the rapid warming of this layer. Above the mixed layer, winds were westerly most of July 16, but they became northerly to northwesterly beginning late on July 16 and continuing through July 17.

At first glance, the unusual conditions revealed by the isentropic analyses suggested that there might have been a problem in the pressure, temperature, and/or altitude data in one or more of the ZIO soundings taken on July 17. The northeasterly winds below 1200 m msl in the 1200 CDT sounding also seemed inconsistent when compared to conditions observed in previous and later soundings. However, the analyses of the data from all six remaining rawinsonde stations indicated that the event captured in the ZIO observations was indeed real and not the result of instrument or operator error. Given the 3-hour sampling interval in the rawinsonde data base, this event appeared to have occurred at about the same time at all the stations except Kankakee, located on the southern end of the network, where the event was delayed by several hours and much weaker. Even the Muskegon analysis showed that similar patterns occurred at about the same time on the east side of Lake Michigan as at the other stations.

In an attempt to explain this phenomenon, we examined satellite imagery, surface and upper air charts, and the rawinsonde and radar profiler data collected by the upper air network during this period. The satellite imagery showed that a mesoscale convective system (MCS) had formed over northern Wisconsin and Michigan on the night of July 16 and early morning of July 17. The rapid cooling in the layer between 2500 m msl and 4500 m msl early on July 17 occurred when the outflow from this storm system advected cool, moist air southward into the study region at mid-levels. The outflow from the MCS also apparently triggered the formation of a weak convergence zone along the southern edge of the main storm complex, along which convective activity subsequently formed.

By 0700 CDT on July 17, the convection had organized into a weak squall line on the southern flank of the storm, which was rapidly approaching the Grafton-Slinger area. Thunderstorms were reported in the area as this system moved southward into the study region. At the same time, a weakly-organized band of convective clouds had formed farther southward, along a line oriented along the Wisconsin-Illinois border, extending eastward toward the Mid-Lake Boat upper air station, then northeastward toward Muskegon. The 0900 CDT satellite image showed that the cirrus shield from the MCS had spread southward to the Wisconsin-Illinois border and indicated that the squall line was moving southward toward the Zion area. By 1000 CDT, the cirrus shield obscured northeastern Illinois, but the squall line appeared to have overtaken and merged with the band of weak convection. In the 1100 CDT satellite image the cirrus shield had largely dissipated, revealing that the line of convective activity was by then definitely south of the Zion area, extending through the Chicago area and across the lower end of Lake Michigan.

Figure 3 shows the 400 m mode profiler data from Zion Shoreline on July 17, 1991. The profiler data provided more detail of the evolution of the flows that accompanied this event. The mid-level outflow from the MCS is evident in the northerly winds observed from midnight until 0500 CDT between 2.5 km and 4 km. The passage of the squall line is seen in the low-level data between 0800 CDT and 1200 CDT, when the winds veered from westerly at 0800 CDT to northwesterly at 0900 CDT to northeasterly by 1100 CDT. These wind patterns are in good agreement with those observed by the Zion 2-Mile rawinsonde station. The onset of the northerly flow observed by the ZIS profiler coincided with the rapid cooling of the lower-levels between 0600 CDT and 0900 CDT shown in Figure 2. Likewise, the return to southwesterly winds at 1300 CDT coincided with the period of rapid warming in the lower levels shown in Figure 2.

The ZIO isentropic analysis indicates that a mesohigh formed over the Zion area as the storm system passed. This conclusion is supported by the anticyclonic wind patterns evident in the profiler data below 2 km from 0900 CDT to 1200 CDT and by a 2 mb pressure rise reported at ZIO from 0600 CDT to 0900 CDT, which was accompanied by a nearly 3°C decrease in temperature at 1 km. Its interesting to note that between the 1200 CDT and 1500 CDT ZIO soundings, the pressure dropped nearly 3 mb at ZIO, while the temperature at 1 km increased more than 4.5°C, suggesting that the mesohigh dissipated quickly.

Figure 4 shows the ozone profiles measured by the Mid-Lake Boat from 1800 CDT on July 16, 1991 through 1800 CDT on July 17, 1991. Although the data below 800 m msl are missing in the 0300 CDT sounding, the concentrations reported in the 0300 CDT sounding show that a fairly substantial reduction in ozone levels from those observed in the July 16 1800 CDT sounding had occurred. By the 1200 CDT sounding on July 17, ozone concentrations had declined even further. It may be that these low ozone levels were due to scavenging of ozone by the storm system that moved through the area the morning of July 17. However, by 1500 CDT ozone concentrations below 800 m msl had increased to nearly 110 ppb; by 1800 CDT ozone concentrations had risen to as high as 120 to 130 ppb. The shape of the 1500 CDT and 1800 CDT ozone profiles, combined with the southwesterly to westerly wind profiles observed at ZIS and ZIO after 1200 CDT, suggest that these ozone levels were caused by transport of ozone produced the same day in the urban areas to the southwest and west. Investigations of this episode are continuing.

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REFERENCES

1. J.L. Haney, S.G. Douglas, L.R. Chinkin, D.R. Souten, C.S. Burton, and P.T. Roberts, Ozone Air Quality Scoping Study for the Lower Lake Michigan Air Quality Region, SYSAPP-89/113, Systems Applications International, San Rafael, CA (1989).

2. N.E. Bowne, P.M. Roth, S.D. Reynolds, C.L. Blanchard, and D.L. Shearer, Lake Michigan Ozone Study Conceptual Design Plan, NB010490, ENSR, Glastonbury, CT (1990).

3. W.L. Ecklund, D.A. Carter, and B.B. Balsey, "A UHF Wind Profiler for the Boundary Layer: Brief Description and Initial Results", J. Atmos. Oceanic Technol., 5: 432-441 (1988).

4. W.L. Ecklund, D.A. Carter, B.B. Balsey, P.E. Currier, J.L. Green, B.L. Weber, and K.S. Gage, "Field Tests of a Lower Tropospheric Wind Profiler", Radio Science (in press).

5. W. Neff, J. Jordan, J. Gaynor, D. Wolfe, W. Ecklund, D. Carter, and K. Gage, "The use of 915 MHz wind profilers in complex terrain and regional air quality studies", in Preprint Volume: Seventh Joint Conference on Applications of Air Pollution Meteorology, Air & Waste Management Association, New Orleans, 1991, American Meteorological Society, Boston (1991).

6. C.G. Lindsey and D.E. Wolfe, "Use of a new generation boundary layer profiler to investigate meteorological processes in complex terrain", paper 91-57.8, 84th Annual Meeting, Air & Waste Management Association, Vancouver (1991).

7. W.D. Komhyr and T.B. Harris, Development of an ECC Ozonesonde, ERL 200-APCL 18, NOAA/ERL, Boulder, CO (1971).

8. T.S. Dye and C.G. Lindsey, "Evaluation of performance of 915 MHz radar profilers and RASS during the 1991 Lake Michigan ozone study", paper 92-68.03, 85th Annual Meeting, Air & Waste Management Association, Kansas City (1992).

9. D.B. Wuertz and B.L. Weber, Editing Wind Profiler Measurements, 438-WPL 92, NOAA/WPL, Boulder, CO (1989).

TABLE 1. Locations of upper air sites and equipment used during the 1991 Lake Michigan ozone study

Site Name	Site ID	Latitude	Longitude	Elevation (m)	Instrumentation
Grafton	GRF	43.34	87.92	236	Radian/STI LAP-3000 & RASS
Slinger	SLI	43.32	88.22	311	Radian/STI LAP-3000
Zion Shoreline	ZIS	42.45	87.80	188	Radian/STI LAP-3000 & RASS
Zion 5-Mile	Z5M	42.45	87.90	209	Radian/STI LAP-3000
Gary	GAR	41.62	87.42	180	Radian/STI LAP-3000
Benton Harbor Airport	BHA	42.13	86.43	190	Radian/STI LAP-3000
Benton Harbor East	BHE	42.07	86.36	207	Radian/STI LAP-3000
Northwest Rockford	ROC	42.46	89.11	225	VIZ W-9000
Zion 2-Mile	ZIO	42.48	87.84	204	VIZ W-9000
Kankakee	KAN	41.07	87.85	188	VIZ W-9000
Muskegon	MUS	43.17	86.24	191	VIZ W-9000
North Lake Boat	BNL	43.30	87.80	177	VIZ W-9000
Mid-Lake Boat	BML	42.47	87.00	177	VIZ W-9000
South Lake Boat	BSL	42.50	87.70	177	VIZ W-9000

TABLE 2. Specifications for the LAP-3000 radar profilers and RASS deployed for the 1991 Lake Michigan ozone study

	Winds	T_v
Averaging Interval	3-60 min	1-10 min
Minimum Altitude	150-200 m agl	100 m agl
Maximum Altitude	1-5 km agl	800-1200 m agl
Vertical Resolution	100 & 400 m	60 & 100 m
Accuracy	--	1°C
Wind Speed	1 m/s	
Wind Direction	10°	

TABLE 3. Instrument specifications for the VIZ W-9000 sounding system and Science Pump, Inc. ozonesonde used during the 1991 Lake Michigan ozone study

Parameter	VIZ W-9000	Ozonesonde
RADIOSONDE		
Model	Mark II	Model 1A
Frequency	403 MHz	N/A
Pressure or O_3		
Range	1080 to 3 mb	Unknown
Accuracy	0.5 mb	5%-10%[7]
Resolution	0.1 mb	1 ppb
Sampling Rate	1.2 sec	1.2 sec
Temperature		
Range	-90°C to +60°C	-90°C to +60°C
Accuracy	0.2°C	0.2°C
Resolution	0.1°C	0.1°C
Sampling Rate	1.2 sec	1.2 sec
Relative Humidity		
Range	5% to 100%	N/A
Accuracy	2.0%	N/A
Resolution	1.0%	N/A
Sampling Rate	1.2 sec	N/A
WINDS		
Position	LORAN-C	N/A
Model	W-9000	N/A
Wind Speed		
Range	min. 0.5 m/s	N/A
Accuracy	0.5 m/s	N/A
Resolution	0.1 m/s	N/A
Averaging Interval	15 sec	N/A
Wind Direction		
Range	1° to 360°	N/A
Accuracy	Unknown	N/A
Resolution	1°	N/A
Averaging Interval	15 sec	N/A

N/A Not applicable

TABLE 4. Summary of data recovery rates for the rawinsonde network during the 1991 Lake Michigan ozone study based on number of scheduled soundings versus number of soundings actually performed

	June 25-28, 1991			July 16-18, 1991			Total		
Site ID	Scheduled	Actual	%	Scheduled	Actual	%	Scheduled	Actual	%
ZIO	30	30	100	22	22	100	52	52	100
KAN	30	30	100	22	22	100	52	52	100
ROC	30	30	100	22	22	100	52	52	100
MUS	30	30	100	22	22	100	52	52	100
BNL	30	13	43	22	20	91	33	52	63
BML	30	20	67	22	22	100	52	42	81
BSL	30	29	97	22	21	95	52	50	96
Total	210	182	87	154	151	98	364	333	91
BML O_3	15	9	60	11	11	100	26	20	77

TABLE 5. Results of audit comparisons between LAP-3000 radar profiler and AV Doppler sodar wind data

			Wind Speed				Wind Direction		
Site	Profiler Alt. (m agl)	No. of Obs.	Avg. Profiler (m/s)	Avg. Diff. (m/s)	rms Diff. (m/s)	Max. Diff. (m/s)	Avg. Diff. (deg)	rms Diff. (deg)	Max. Diff. (deg)
Mode: 100 m									
GRF	123	2	3.9	-0.5	0.8	-0.6	-35.0	35.0	-41.0
	225	6	4.6	0.6	0.8	1.8	-9.0	19.0	28.0
	326	7	4.6	0.4	0.8	1.3	-14.0	23.0	-48.0
	427	1	4.0	0.7	1.0	1.9	-36.0	41.0	-69.0
	529	4	3.0	0.1	0.1	0.1	8.0	8.0	8.0
SLI	123	5	5.1	-0.8	1.2	-2.0	-24.0	25.0	-31.0
	225	16	8.8	0.2	2.3	-5.3	-1.0	7.0	16.0
	326	8	6.1	-1.5	2.6	-6.3	-6.0	8.0	-12.0
	427	6	6.4	-1.8	2.6	-5.3	-9.0	13.0	-17.0
ZIS	225	14	4.0	-0.6	1.3	-2.5	2.0	12.0	34.0
	326	12	5.5	0.4	1.3	-2.6	-5.0	10.0	-19.0
	427	11	6.3	1.0	1.7	3.1	-3.0	8.0	-15.0
	529	1	8.7	2.7	2.7	2.7	-3.0	3.0	-3.0
ZI5	210	5	5.8	1.5	1.9	3.2	14.0	21.0	27.0
	311	8	5.1	0.4	0.8	1.7	6.0	12.0	26.0
	413	8	5.5	0.3	0.5	0.8	16.0	20.0	37.0
	514	3	7.7	1.1	1.2	1.4	9.0	12.0	17.0
	616	2	8.0	1.3	1.3	1.6	9.0	10.0	14.0
GAR	254	10	10.9	0.4	1.2	1.9	-1.0	3.9	-7.0
	355	3	10.5	0.9	1.7	2.3	-3.0	3.6	-6.0
	456	3	8.2	0.5	0.9	1.3	-4.0	7.3	-12.0
BHA	152	8	4.5	-0.8	1.2	-2.3	-11.0	13.7	-24.0
	254	10	5.0	0.3	0.9	1.6	-11.0	12.0	-17.0
	355	10	5.1	0.0	1.1	2.1	-6.0	9.7	-16.0
	456	8	5.2	0.2	0.8	1.2	-8.0	10.0	-14.0
	558	1	4.3	0.7	0.7	0.7	-17.0	17.0	-17.0
BHE	152	9	7.4	1.1	1.2	2.0	0.0	9.2	19.0
	254	10	8.9	0.5	0.7	1.4	2.0	6.2	15.0
	355	10	9.3	0.5	0.9	2.0	1.0	5.2	12.0
	456	10	9.6	0.6	0.9	1.8	-4.0	10.0	-30.0
	558	7	10.6	1.1	1.6	3.5	-2.0	4.2	-7.0
	659	4	11.9	1.4	1.4	1.7	-3.0	3.7	-6.0
	761	2	12.2	2.0	2.1	2.7	-7.0	7.0	-9.0
Mode: 400 m									
GRF	188	8	3.9	-0.1	0.5	0.8	-25.0	27.0	-43.0
	391	7	4.6	0.8	1.2	2.7	-22.0	31.0	-69.0
	594	2	3.2	-0.3	0.7	-1.0	6.0	12.0	16.0
SLI	391	8	5.7	-2.2	3.0	-6.0	-9.0	11.0	-19.0
ZIS	390	9	5.9	0.5	1.0	2.1	-4.0	6.0	-12.0
ZI5	580	4	7.9	1.8	2.0	3.1	17.0	22.0	40.0
GAR	391	4	9.3	0.4	1.0	1.8	-4.0	6.6	-13.0
BHA	188	7	5.1	-0.4	0.8	-1.3	-4.0	8.2	13.0
	391	10	5.2	0.2	1.1	2.2	-3.0	7.8	-15.0
	594	1	4.7	1.1	1.1	1.1	-1.0	1.0	-1.0
BHE	391	9	10.3	1.4	1.7	3.0	3.0	11.0	20.0
	594	6	10.9	0.4	0.7	1.1	-2.0	6.0	9.0
	797	2	10.8	0.7	0.9	0.8	-8.0	8.3	-11.0

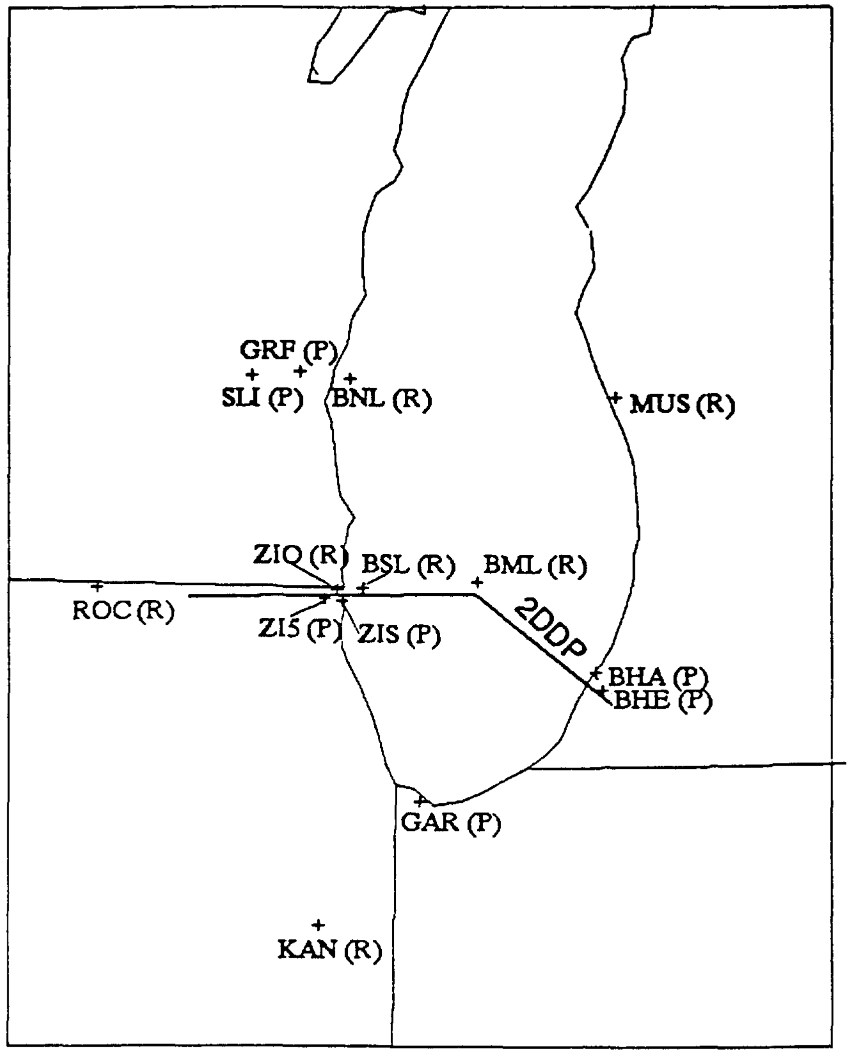

FIGURE 1. Distribution of sites in the LMOS upper air network and location of the 2 DDP; "P" indicates a profiler site and "R" signifies a rawinsonde station.

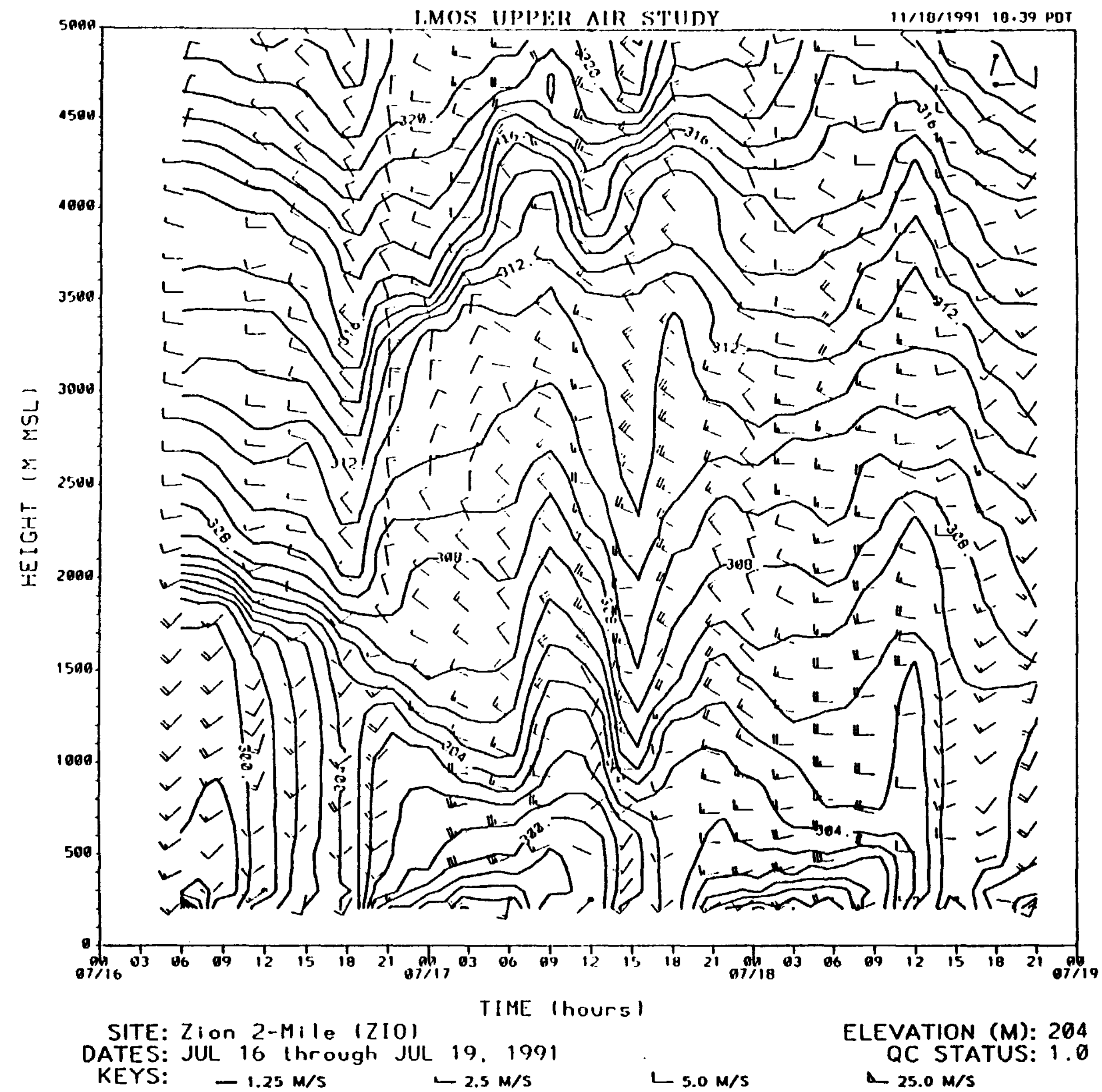

FIGURE 2. Time-height cross-section of winds and contours of potential temperature (isentropes) based on data collected at Zion 2-Mile during the 2nd IOP (July 16-18, 1991).

92-87.07

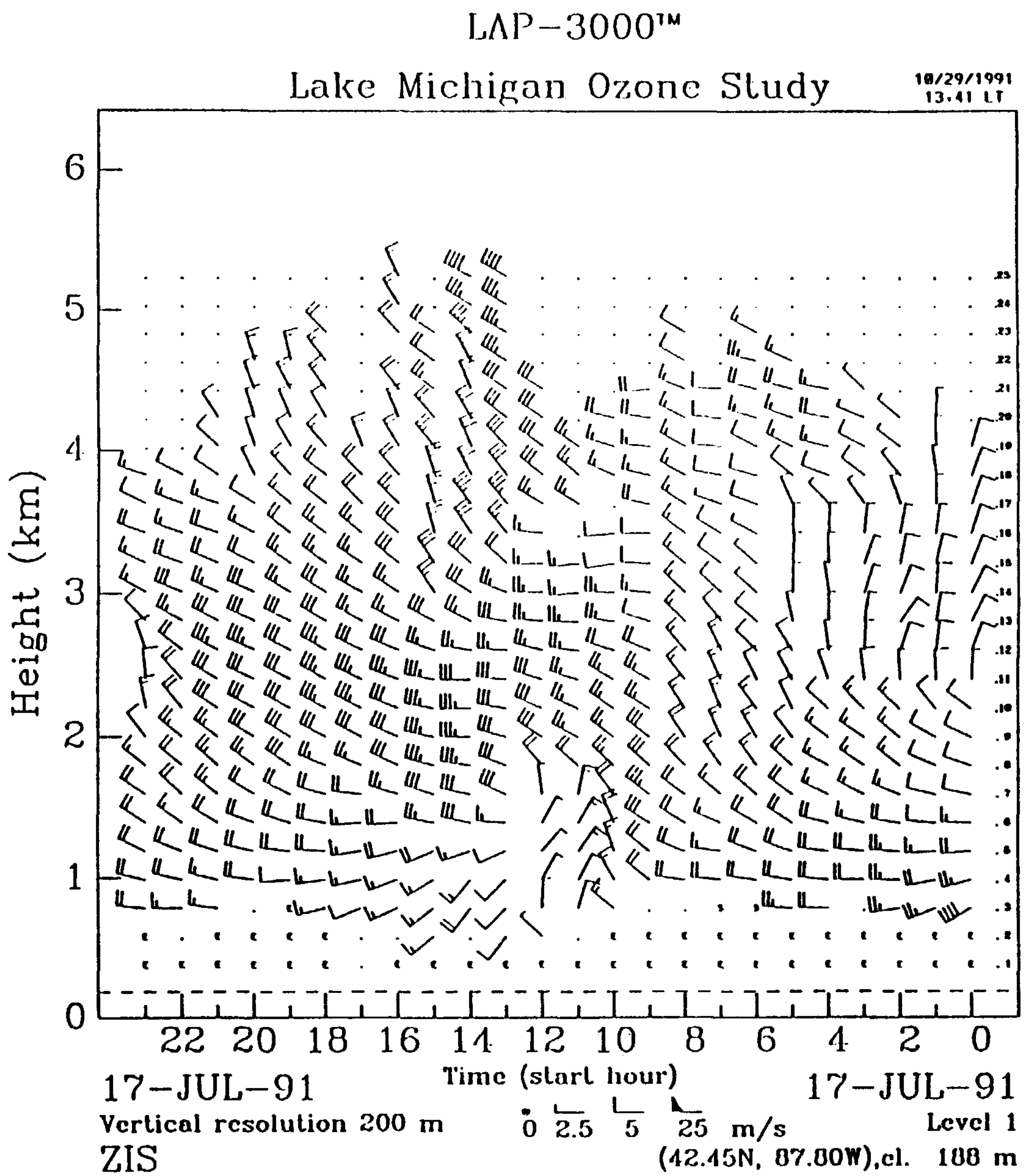

Figure 3. Time-height cross-section of winds measured at Zion Shoreline on July 17, 1991 during the 2nd IOP.

92-87.07

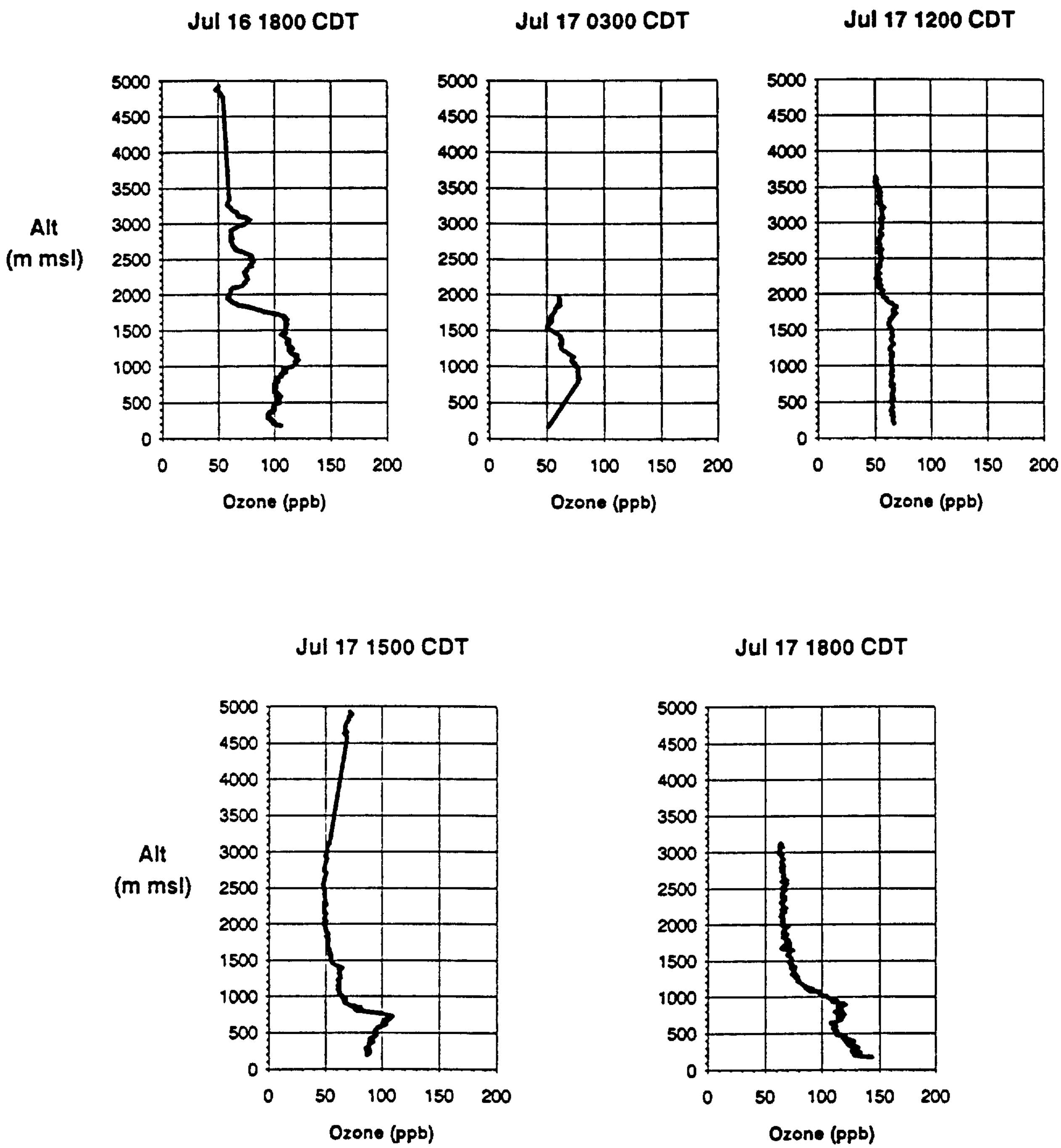

Figure 4. Ozone profiles recorded on the mid-lake boat from 1800 CDT July 16, 1991 through 1800 CDT July 17, 1991.

APPENDIX E

Use of a New Generation Boundary Layer Profiler to Investigate Meteorological Processes in Complex Terrain

By:

Charles G. Lindsey
Sonoma Technology, Inc.

and

Daniel E. Wolfe
National Oceanic and Atmospheric Administration

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Charles G. Lindsey
Sonoma Technology, Inc.
Santa Rosa, California

Daniel E. Wolfe
National Oceanic and Atmospheric Administration
Boulder, Colorado

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INTRODUCTION

During the past few years, research staff from the Aeronomy Laboratory (AL) and Wave Propagation Laboratory (WPL) of the National Oceanic and Atmospheric Administration's (NOAA) Environmental Research Laboratories (ERL) have been developing a small, portable, PC-based Doppler radar profiler for measuring clear-air winds in the lower troposphere[1,2,3]. Operating at a frequency of 915 MHz, this profiler measures radial wind components as a function of altitude using a three-axis antenna configuration. One antenna is aimed vertically to measure vertical velocities, while the other two antennas, which are oriented at right angles to each other, are aimed at approximately 15 degrees from the zenith to measure orthogonal radial velocity components. From these three radial velocities, horizontal winds (speed and direction) as a function of altitude are computed. The principles of operation of the 915 MHz profiler are similar to those of the deep tropospheric profilers operating at 50 MHz or 404 MHz[4]. The radar signal is scattered by inhomogeneities in the index of refraction in the clear atmosphere, and some of this energy is scattered back to the antenna. By determining the Doppler shift of the returned signal, the velocity component along the axis of each antenna can be calculated, from which the horizontal wind speeds and directions are computed. With appropriate algorithms to account for fall velocities, winds aloft are also calculated during precipitating conditions.

The current design of the 915 MHz profiler allows sampling of the winds as a function of altitude to heights of one to four km agl, depending on atmospheric conditions. The lowest altitude at which winds can be measured is approximately 60 to 100 m, and the vertical resolution is also 60 to 100 m, depending of how the radar is configured to operate. Thus, this instrument is designed to measure winds aloft within and above the planetary boundary layer (PBL), and has been nick-named the "boundary layer profiler" (BLP). Typically, the BLP is configured to provide hourly-averaged wind profiles on a continuous basis (data needed to calculate winds with finer temporal resolution, such as 2- to 5-minute averages, are also available).

An important application for the boundary layer profilers is the routine, continuous collection of data that can be used to evaluate transport regimes for air quality studies. Neff et al.[5] report on how these profilers have been used in several recent air quality studies conducted in complex terrain environments. One of these studies was the Salt River Project's (SRP) Navajo Generating Station (NGS) Winter Visibility Study, where three profilers were operated in northern Arizona during the period January 10, 1990 to March, 31 1990. Data from these profilers and other measurement systems were used to analyze transport regimes within and above the complex topography of the study area. The purpose of this paper is to explain how the profilers were operated during the study, to describe some of the ways in which the profiler data have been used in the analyses of the transport of emittants from NGS, and to show some of the effects of the terrain of the Grand Canyon region on local flows that were revealed by the profiler data.

THE 1990 NGS WINTER VISIBILITY STUDY AND OPERATION OF THE RADAR PROFILERS

The objectives and design of the 1990 NGS Winter Visibility Study are described in detail by Richards et al.[6,7]. Briefly, the objective of the study was to determine the contribution of emittants from NGS (especially SO_2, which may then be oxidized to SO_4 aerosol) to visibility impairment at the Grand Canyon during the winter and to estimate the improvement in wintertime visibility that would occur if SO_2 emissions from NGS were reduced. The experiment included a number of meteorological measurements that were designed to monitor wind and stability conditions in the major topographic channels of the study area and to support analyses of the mechanisms responsible for transporting NGS emittants through the region[8]. Figure 1 shows the locations of the meteorological monitoring sites within the study area. Note that in addition to the profilers, upper air data were collected intermittently by rawinsonde, tethersonde, and Airsonde sounding systems at eight sites and continuously by Doppler sodars at four stations. In addition, a network of fifteen surface stations measured winds, temperatures, moisture, and other parameters continuously during the field study.

A suite of surface and aloft chemistry and visibility measurements were also collected during the study[6,7]. An important component of the study was the release of perfluorocarbon tracers continuously from the stacks of the NGS. Four different tracers were used, one each day during a four day cycle, at which time the cycle would be repeated. The tracer being emitted was changed at 1800 MST each day. The amount of tracer released was proportional to the rate of release of SO_2; the ratio of tracer-to-SO_2 was monitored continuously. Ground-level tracer concentrations were sampled by a network of surface stations on a daily basis (four-hour integrated samples); aloft concentrations were sampled intermittently by research aircraft during intensive operational periods (IOPs), which were called based on weather and pollutant forecasts.

The three radar profilers were located at Page (PGA), near the Navajo Generating Station; at Cedar Ridge (CDR), along the Marble Canyon plain; and at Phantom Ranch (PTN) at the bottom of the Grand Canyon. The Page site was chosen because continuous wind measurements were needed over the range of altitudes at which the NGS plume would be found; these data would be used to monitor the transport of fresh emittants from NGS within the Lake Powell basin. The Page data were also needed to document the evolution of terrain-forced mesoscale circulations that had been observed previously in the Lake Powell basin[9]. Of special interest was the possibility that these circulations might form in the lower part of the boundary layer and that the winds in this layer might be de-coupled from the winds at plume-carrying altitudes. In this event, emittants mixed into the lower PBL might be transported by flows that were markedly different than those at plume heights. Cedar Ridge was chosen as a profiler site so that flows along the Marble Canyon plain between Page and the Grand Canyon could be monitored. Continuous data in and above the boundary layer were desired at this site in part to examine the effects of the Kaibab Plateau on the evolution of the winds along this major topographic channel (e.g., development of diurnal slope and valley circulations, terrain channeling of winds, etc.). The Kaibab Plateau runs approximately north-northeast to south-southwest along the western edge of Marble Canyon. The third profiler was placed at Phantom Ranch in the first known attempt to routinely monitor the wind fields through the full depth of the Grand Canyon itself.

Data Collection

Sonoma Technology Inc. (STI) acted as the overall coordinator of the meteorolgical component of the field study and was specifically responsible for operation of the surface and rawinsonde network deployed for the study. The three profiler sites were deployed and maintained by staff from NOAA/ERL/WPL. The Page and Phantom Ranch sites were operational by January 10, 1990. The Cedar Ridge site became operational on January 12, 1990. The data from each site were collected by WPL staff on a regular basis and returned to WPL for additional processing. Operations were discontinued at Phantom Ranch after March 19, 1990. The Page and Cedar Ridge profilers continued to operate through the end of the study on March 31, 1990.

Each profiler was controlled by a PC-based personal computer. Data collection involved transmitting a radar signal with a specific pulse length from each antenna and then "listening" for the back-scattered signal at discrete intervals, or range gates. The pulse length and listening interval determined the sampling volume, the altitude of each gate, and the maximum altitude to which valid data could be collected. The profilers were run in two modes for the NGS study. In the first mode, the pulse length was set to 100 m, which gave a vertical resolution and sampling volume of 100 m. The maximum altitude obtained in this so-called "low mode" was typically 1000 m agl to 1500 m agl. The second mode used a 400 m pulse length, which allowed data to be obtained to higher altitudes although the averaging volume was larger (i.e., 400 m). Wind data in this so-called "high mode" were computed with a 100 m vertical resolution by overlapping the return signal from sequential range gates. In this way, data were obtained to as high as 4000 m agl under good conditions. .The radar automatically cycled between these two modes, sampling for approximately 30 seconds in each mode for each of the three antennas.

Software running on the computer determined the first moment, or peak signal, of the spectrum of the returned signal for each range gate in each of the two modes. From these moments, the Doppler shift and then the radial velocity components were calculated for each axis (antenna) of the radar. The signal from each antenna was averaged for 30 s to 60 s before the moments were calculated. The data acquisition system stored the moments on the PC's hard disk in MS-DOS binary files. Theres data were routinely backed-up to floppy diskettes by field technicians for later processing as required. From these 30 s to 60 s averaged moments, the hourly averaged wind speeds and directions were computed for each mode. The hourly-averaged data were stored as ASCII text files on the PC's hard disk and backed-up onto floppy diskettes. The data also were printed on a dot matrix printer at the site as an additional precautionary back-up and for review by the technicians when they visited the field sites to check the status of the profilers.

Quality Control

The data acquisition software that controlled the operation of the profilers also performed preliminary quality control screening of the data before final hourly-averaged winds were computed. Consensus averaging of the winds was based on obtaining a user-specified number of valid spectral moments for each of the three antennas. The software attached preliminary quality control flags to each set of wind data, depending on the number of spectral moments used in the wind computation.

Further processing was performed on the data after they were returned to WPL, which included data editing and quality control screening by software developed by ERL research staff[10,11]. These software packages checked the spatial and temporal consistency of the wind data to identify possible outliers or other problems with the wind observations. In addition to reviewing the wind observations themselves, the software screening used quality control parameters, which were generated by the data acquisition system at the time the data were collected, to identify possible errors in the data (e.g., signal-to-noise ratios as a function of altitude for each antenna). Once the software screening was completed, a trained meteorologist who was familiar with profiler principles and operations reviewed the data. When his review was completed, the profiler observations were released as Level 1 validated data. Each data point included a quality control flag that identified the data point as valid, invalid, or missing. If a data point was flagged as invalid, the flag also indicated the cause of the problem (e.g., insufficient number of spectral moments to calculate a valid hourly-averaged wind).

USES OF PROFILER DATA FOR ANALYZING THE TRANSPORT OF EMISSIONS FROM NGS

The data collected by the radar profilers were used to support a number of investigations into the meteorological processes affecting the transport of emissions from NGS. One objective of these analyses was the need to identify periods when emittants from NGS may have been present at the Grand Canyon and to explain the mechanisms responsible for their transport to the Canyon. An important issue addressed by these analyses was the identification of conditions when the transport regimes were driven principally by the synoptic-scale pressure gradients across the region versus conditions when mesoscale circulations may have formed in response to terrain-induced flows.

Coupling and De-coupling of Air Flows in the Study Area

Figure 2 shows twenty-four hours of wind data measured by the Page radar profiler on January 17, 1990. These results are an example of conditions when the winds at plume-carrying altitudes (typically 600 to 800 m agl) were driven by the synoptic-scale pressure gradient, which in this case was associated with a closed low pressure system that began moving into the study area on the 17th. Winds through the depth of the boundary layer were reasonably well coupled with the flows at higher altitudes in the early morning hours of January 17, 1990. There is little evidence of terrain-induced flows in these data. At the same time, these results also show how dynamically and quickly transport conditions can change in northern Arizona during the winter. Prior to 1000 MST, the winds were southerly to southwesterly from the surface through the depth of the PBL, in response to the cyclonic circulation around the low that was still southwest of Page. However, as the low approached Page, winds in the first few hundred meters of the boundary layer suddenly began backing to easterly at 1000 MST while the winds at plume height were still southerly. Emissions from NGS mixed into the lower parts of the boundary layer were being transported to the west, even while the main plume was still being transported to the north. By approximately 1600 MST, the winds aloft were easterly throughout the depth of the PBL as the closed low moved into the study area, and the emittants from NGS were being carried to the west.

An example of de-coupled conditions induced by the complex terrain of the study area occurred on January 21 and 22. A ridge of high pressure had built over northern Arizona following the passage of the low pressure system, accompanied by a strong inversion and subsiding dry air over the study area. Isentropic analyses were performed to investigate this event in detail because it was a period when emittants from NGS reached the

Grand Canyon. Figure 3 is an isentropic cross-section between Bullfrog Basin and Ash Fork at 1600 MST on January 21, 1990. Levels of constant potential temperature (isentropes) were computed from rawinsonde and Airsonde ascents performed at Bullfrog Basin (BUL), Dangling Rope (DNG), Page (PGA), Cedar Ridge (CDR), Phantom Ranch (PTN), Tusayan (TUS) and Ash Fork (ASH). These levels are plotted in Figure 3 as a function of altitude, along with the vertical wind profiles from the three radar profilers (PGA, CDR, PTN) and the from the rawinsonde soundings at BUL, TUS and ASH. The wind data reported at Dangling Rope were collected by Doppler sodar. The dashed lines are isopleths of constant relative humidity. The solid dark line plotted in the figure represents the altitude of the terrain along the path of the cross-section. The star above Page represents the estimated altitude of the plume from NGS, based on the Briggs[12] plume rise algorithm.

As shown in Figure 3, the atmosphere inside the Lake Powell basin (BUL, DNG, PGA) was moderately stable. The base of the subsidence inversion was located at approximately the altitude of the highest terrain along the path of the cross-section. At this time, the inversion extended from approximately 2200 m msl to 2700 m msl. Winds in and above the inversion were generally easterly, circulating in a clockwise (anticyclonic) manner around the center of the high pressure system. Below the inversion, however, winds regimes inside the Lake Powell basin, Marble Canyon plain, and the Grand Canyon were de-coupled from the easterly flows aloft. In the lower parts of the PBL above Page, the winds were northeasterly, towards the Grand Canyon. The winds at Cedar Ridge below the top of the Kaibab Plateau were northerly, probably due to channeling of air flows along the face of the Plateau. The winds near the rim of the Grand Canyon above Phantom Ranch were coupled with the synoptic-scale flows aloft, but at lower altitudes there was a layer of westerly, up-Canyon winds near the bottom of the Canyon and southerly winds at mid-levels.

Figure 4 shows the isentropic analysis twelve hours later at 0400 MST on January 22, 1990. The inversion had descended into the Lake Powell basin, across the Marble Canyon plain, and the into the Grand Canyon itself. Winds in the free atmosphere above the inversion were generally southerly, but winds inside the terrain were markedly de-coupled from these synoptic-scale flows. The Page profiler and Dangling Rope sodar both showed low-level easterlies in the Lake Powell basin. Winds in the Grand Canyon were now down-Canyon. The implication of these features on the transport of NGS emittants is discussed in the next section.

Transport of NGS Emissions Estimated from Profiler Data

One of the techniques used to analyze the transport of emissions from NGS was to calculate air parcel trajectories starting at Page for each hour of the study period at several altitudes where emittants were expected to be present. These trajectories were computed from objectively analyzed, mass-consistent wind fields that were themselves calculated for each hour of the study period from January 10, 1990 through March 31, 1990. The wind fields were computed using a pair of kinematic wind field models developed at the California Institute of Technology by Goodin, et al.[13] and later modified by the California Air Resources Board. A two-dimensional model calculated gridded surface winds by interpolating the hourly-averaged data collected by the network of surface stations shown in Figure 1. Aloft wind fields were calculated by a three-dimensional model, using the output of the surface model and the hourly-averaged profiler and sodar wind data and wind observations from the rawinsonde ascents, which were collected either two or four times per day, depending on whether or not an IOP was underway. The three-dimensional model first calculated interpolated wind fields at user-specified altitudes and then adjusted these wind fields to obtain mass balance by application of the incompressible form of the continuity equation. Missing data were interpolated linearly in time in both the surface and upper air models; a cubic polynomial was used to interpolate missing data in the vertical in the upper air model. Lindsey et al.[8] discuss the wind field and trajectory modeling in more detail.

From the wind field analyses, forward trajectories of air parcels starting each hour above Page were calculated for 300 m agl, 600 m agl, and 750 m agl to simulate the transport of emittants from NGS at typical plume carrying altitudes. From the trajectory analyses, streak lines were then prepared to represent the "centerline" of the NGS plume at each hour of the study from January 10 at 0000 MST to March 31 at 2300 MST. (In the strictest sense, a streak line defines the line at a particular moment in time connecting all air parcels that have passed a given geometric point, in this case 300 m agl, 600 m agl, and 750 m agl above Page.) The results of these streak lines were displayed in a computer animation, along with tracer and SO_2 data collected by a network of surface sampling stations in the study area[8]. The tracer and SO_2 data were reported as four-hour integrated samples.

Figure 5 shows one frame of the animation, valid at 2200 MST January 21, 1990, mid-way between the two isentropic cross-sections presented in Figures 3 and 4. The streak lines are represented by circles whose diameter is proportional to twice the integrated distance travelled by the trajectories that underlie the streak lines. Specifically, the diameter of each circle is given by:

$$\text{Diameter} = 2X^{0.8}$$

where X is the cumulative distance traveled from Page[14]. This very simple parameterization is not designed so much to be a representation of plume dispersion as it is to be a mnemonic for the "age" of the simulated air parcel. The tracer and SO_2 data are represented by the bar graphs shown in the figure. Forty-eight hours of hourly-integrated nephelometer readings and hourly-averaged relative humidity data from Hopi Point, centered on 2200 MST, are shown in the "strip chart" display in the lower right corner of the figure.

As shown by the tracer and SO_2 data, emittants from NGS were present both at Fredonia, due west of Page, and along the Marble Canyon plain to the southwest of Page. The 600 m agl streak line indicates that the transport to the west was due to the easterly flows from the Lake Powell basin below the base of the inversion. As revealed by the 300 m agl streak line however, the transport to the southwest along the Marble Canyon plain appears to have occurred at lower altitudes, below the top of the terrain. The profiler data presented in the isentropic cross-sections in Figures 3 and 4 showed westerly transport above Page at the altitude of the Briggs plume rise estimate, but also revealed northeasterly winds at lower altitudes and channeling of the winds along the Marble Canyon plain below the top of the Kaibab Plateau. The wind field and trajectory analyses, which used these observations, and independent tracer and SO_2 data confirmed that indeed part of the plume from NGS was blocked by the high terrain west of Page and diverted along the Marble Canyon towards the Grand Canyon, while portions of the plume at higher altitudes were transported away from the Grand Canyon, westwards through the Fredonia Pass.

The results presented in Figure 5 suggest that the high degree of temporal and spatial resolution provided by the radar profilers was helpful in identifying conditions when the transport of emittants from NGS was strongly affected by the complex terrain of the region. The sensitivity of the wind field and trajectory models to the resolution provided by the profilers was examined by re-analyzing the data from a ten day period in January when both coupled and de-coupled conditions existed in the study area. Specifically, the three-dimensional wind field and trajectory computations were repeated for the period January 15 through January 25, but only two profiles of wind data from the radar profilers and sodars were used rather than the full 24 hours included in the original analyses. Only data from 0400 MST and 1600 MST were used, which were the same sampling periods used by the rawinsonde and Airsonde stations on non-IOP days. The wind field model used linear interpolation to estimate the observations at the missing hours. Once the trajectories were re-computed, the differences between the positions of the air parcels from each set of trajectories as a function of elapsed time were calculated. These tests showed that indeed the model-predicted locations of the air parcels were sensitive to the resolution of the wind data, especially under de-coupled conditions when terrain-induced flows occurred. For example, after 24 hours of transport, the average differences between the predicted positions of air parcels calculated from the full-resolution data set versus the twice-daily data set were 50 km to 85 km, and exceeded 150 km in some cases. Under relatively steady, coupled conditions where the assumption of linear variations in the winds with time might be more reasonable, the differences were sometimes as small as a 10 - 15 km after 24 hours of transport.

SUMMARY

A network of three boundary layer radar profilers was deployed as part of the meteorological monitoring component of the 1990 NGS Winter Visibility Study. This was one of the first uses of this new generation of profilers to investigate meteorological processes in a complex terrain environment and how these processes affect the transport of air pollutants. The profilers provided a relatively simple, accurate means to monitor winds aloft on a continuous basis in the first one to four kilometers of the atmosphere. The instruments are relatively small and light, which makes them simple to transport and deploy for studies such as the NGS Winter Visibility Study. Data collection is well-automated and quality control algorithms developed by NOAA/ERL staff appear to work well in identifying and flagging questionable data produced by weak signal reception or sources of interference (e.g., ground clutter, aircraft, birds, etc.).

The profilers used during the SRP field study revealed a number of interesting features in the flow fields of the lower atmosphere in the region of the Grand Canyon, including de-coupling of the winds in the lower PBL from the synoptically-driven winds aloft and terrain channeling of air flows, among others. The high degree of temporal and spatial resolution in the profiler data allowed relatively simple wind field and trajectory models to be used to locate emissions from NGS with a high degree of success. The results presented in this paper are only a sample of the investigations that have been performed using these data.

Since the 1990 NGS Winter Visibility Study, new refinements have made by NOAA staff to the hardware and software of the boundary layer profilers. New ground clutter suppression fences have improved data recovery, as have changes to the ground clutter algorithms in the software. A Radar Acoustic Sounding System (RASS) has been added to the profilers to remotely measure temperature profiles in approximately the first 1000 m agl of the atmosphere. With these additions and ones still being developed (e.g., pulse "coding" via phase changes, which eliminates the need to operate in different modes to obtain different vertical resolutions), the boundary layer radar profilers are an effective tool for studying meteorological processes affecting air quality in a variety of settings.

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REFERENCES

1. W.L. Ecklund, D.A. Carter, and B.B. Balsey, "A UHF wind profiler for the boundary layer: Brief description and initial results", J. Atmos. Oceanic Technol., 5, 432-441 (1988).

2. W.L. Ecklund, D.A. Carter, B.B. Balsey. P.E. Currier, J.L. Green, B.L. Weber, and K.S. Gage, "Field tests of a lower tropospheric wind profiler", Radio Science (in Press).

3. D.E. Wolfe, W.L. Ecklund, D.A. Carter, and K.S. Gage, "Evaluation of performance of NOAA's 915 MHz boundary layer radar during the 1990 Grand Canyon Visibility Study", in Preprint Volume: Seventh Joint Conference on Applications of Air Pollution Meteorology with AWMA, held January 13-18 1991 at New Orleans LA, Amer. Meteorol. Soc., Boston (1991).

4. D.W. van de Kamp, Profiler Training Manual #1 Principles of Wind Profiler Operation, Profiler Program, NOAA/ERL, Boulder, Colorado (1988).

5. W. Neff, J. Jordan, J. Gaynor, D. Wolfe, W. Ecklund, D. Carter, and K. Gage, "The use of 915 MHz wind profilers in complex terrain and regional air quality studies", in Preprint Volume: Seventh Joint Conference on Applications of Air Pollution Meteorology with AWMA, held January 13-18 1991 at New Orleans LA, Amer. Meteorol. Soc., Boston (1991).

6. L.W. Richards, et al., Navajo Generating Station Visibility Study Status Report, Working Draft Number 4, STI-99281-1001-WD4, August, 1990. Prepared for Salt River Project, Phoenix, AZ, by Sonoma Technology, Inc., Santa Rosa, CA (1990).

7. L.W. Richards, et al., Navajo Generating Station Visibility Study Final Report Draft Number 2, STI-90200-1124-FDR2, April, 1991. Prepared for Salt River Project, Phoenix, AZ, by Sonoma Technology, Inc., Santa Rosa, CA. (1991).

8. C.G. Lindsey, J. Chen, and T.S. Dye, "Meteorological processes affecting transport of emissions from the Navajo Generating Station", Paper No. 91-47.8, 84th Annual Meeting, Air & Waste Management Association, Vancouver (1991).

9. R.C. Balling and J.L. Sutherland, "Diurnal and seasonal wind direction patterns within the mountain-valley terrain near Glen Canyon Dam, Arizona", J. Appl. Meteor., 27(5):594 (1988).

10. K.A. Brewster, Profiler Training Manual #2 Quality Control of Wind Profiler Data, Program for Regional Observing and Forecasting Services (PROFS), NOAA/ERL/FSL Boulder, Colorado (1989).

11. D.B. Wuertz and B.L. Weber, Editing Wind Profiler Measurements, NOAA Technical Report ERL 438-WPL 92, NOAA/WPL, Boulder, Colorado (1989).

12. G.A. Briggs, "Chimney Plumes in Neutral and Stable Surroundings", Atmos. Env., 6, 507-510 (1972).

13. W.R. Goodin, G.M. McRae, and J.H. Seinfeld, "An Objective Analysis Technique for Constructing Three-Dimensional Urban-Scale Wind Fields", J. Appl. Meteor., 19(1):98 (1980).

14. T.B. Smith, "Some observations of pollutant transport associated with elevated plumes", Atmos. Eviron., 15:2197-2203.

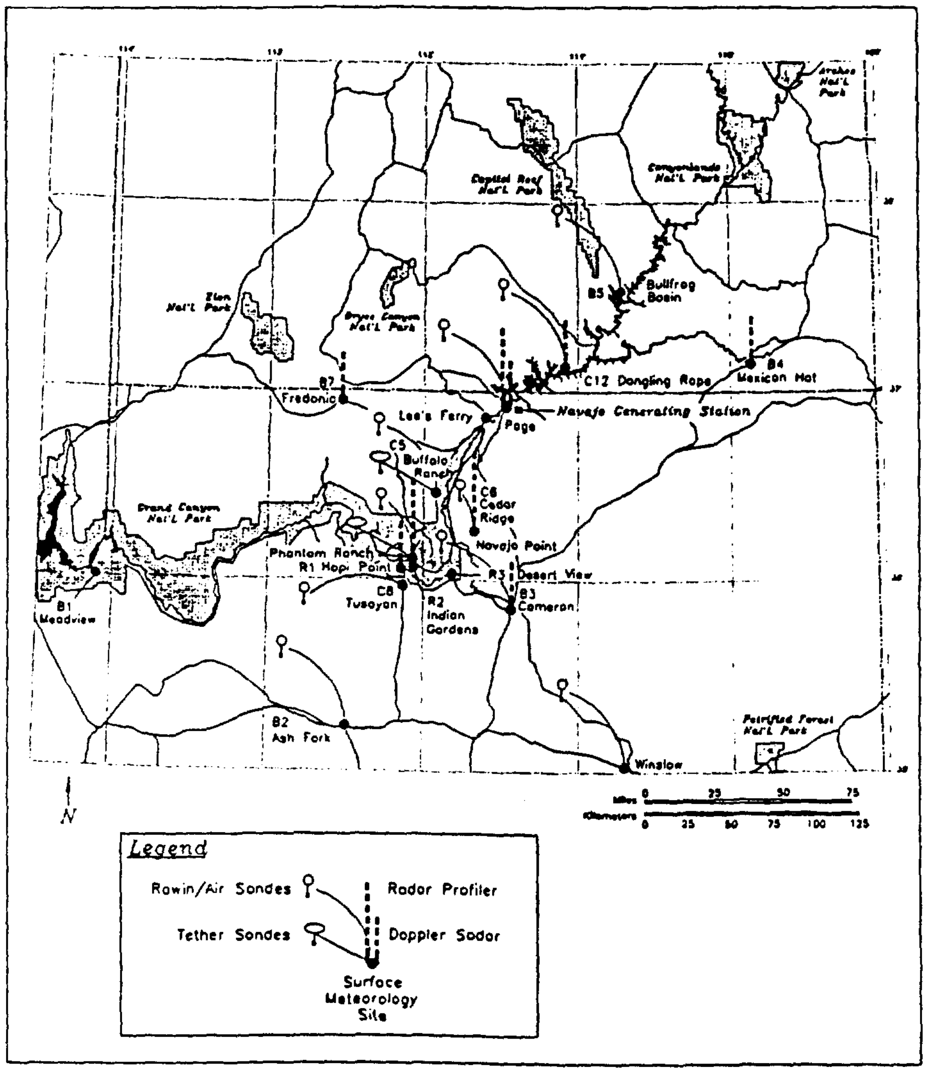

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Figure 1 Map of the study region and locations where surface and upper air meteorological data were collected.

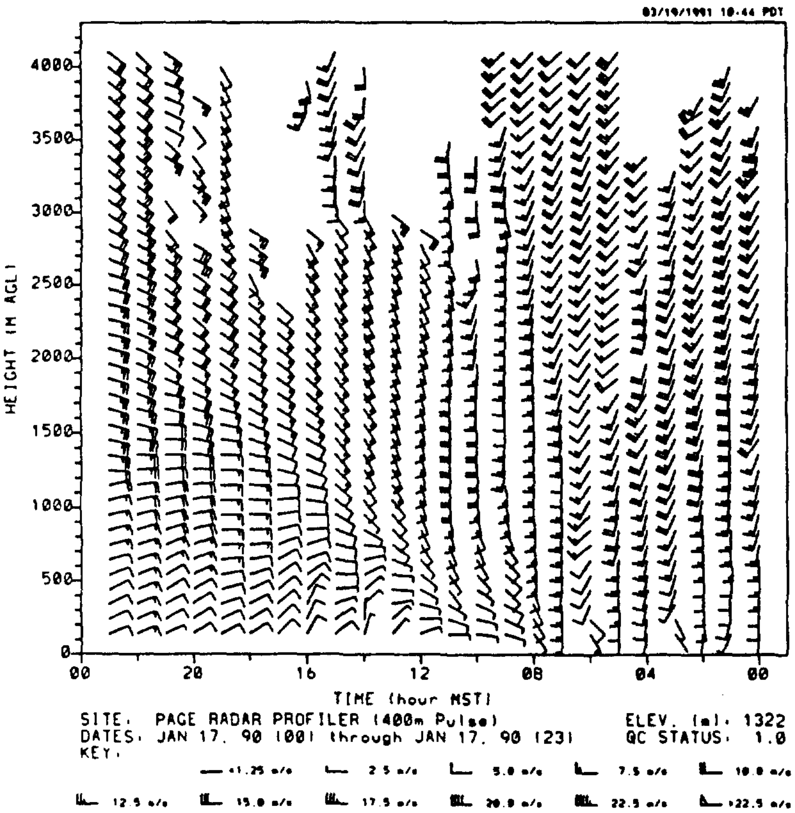

Figure 2 Time-height cross-section of winds measured by the Page radar profiler on January 17, 1990; time increases from right to left in the figure; see key for explanation of wind barb format.